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Advanced Solid-State Lasers

To Ignition and Beyond...

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About the cover

This broshue concentrates on the diode-pumped solid-state laser. Surrounding it on the cover are some of the primary technological developments that make it a candidate for the means by which inertial confinement fusion will create inertial fusion energy as an inexhaustible source of electric power. Clockwise from the upper left are: a ytterbium-doped stronium-fluorapatite (Yb:s-FAP) crystal from which the laser's gain element is made; a diode array, the source of laser's pump light; a single laser diode package; a Yb:S-FAP crystal; and a lens duct.

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The Next Frontiers of Advanced Lasers Research

When the National Ignition Facility comes on-line in 2003, it will represent the conclusion of one process and the beginning of others. It will be the culmination of more than a decade of research and development to achieve laser ignition—the implosion in a laboratory environment of a small, hydrogen-isotope-filled target by laser beams of sufficient energy and quality to create, for a micro-instant, inertially confined fusion—a process comparable to that at the center of the sun. Simultaneously, it will represent the beginning of other quests, among them to fulfill the ultimate civilian goal of NIF—taking lasers beyond NIF to enable them to create inertial fusion energy, a low-cost, inexhaustible supply of electric power through repeated, sustained laser ignition and fusion energy gain.

Lawrence Livermore National Laboratory recognized and embraced the challenge of taking lasers beyond NIF more than a decade ago, even before NIF was specifically defined. The Laboratory made the early commitment to identify and develop the concepts and technologies that would propel laser applications beyond NIF because we know that the design, development, and construction of each major new experimental program facility take at least 10 years or more. Therefore, positioning large-scale programs to be able to explore the frontiers of new knowledge calls for the earliest possible anticipation of program facility needs and the timely development of the necessary enabling technologies.

In the case of NIF, these research management principles have meant that as the Laboratory solved the scientific problems and developed the technology to make NIF a reality, we almost concurrently had to do the science and provide the technology to take lasers beyond NIF.

Two articles in this issue of Science & Technology Review report on developments that not only will help inertial fusion achieve its immediate goal—ignition—but may provide the enabling technology to make lasers the means of providing inertial fusion energy.

The feature article, “Taking Lasers beyond the National Ignition Facility,” beginning on p. 4, makes the compelling point that the flashlamp-pumped neodymium-doped glass (Nd:glass) lasers that NIF will use to create fusion ignition represent several decades of development and scaling. Flashlamp-pumped solid-state lasers have been developed worldwide as the workhorse laser driver of choice for single-shot inertial confinement fusion and high-energy-density research facilities at Livermore and elsewhere. Yet, it was generally believed that solid-state lasers as a class lacked other qualities necessary to effectively drive an inertial fusion energy reactor—namely, the capability to generate fusion-like, megajoule pulse energies simultaneously with output beams characterized by high quality, high pulse-repetition rate (about 10 hertz), and high efficiency (greater than 10%). The article goes on to discuss the conceptual and technological innovations that overcame this long-held perception. It focuses on the part the Laboratory played in developing (concurrently with NIF) the enabling laser technology advances that make diode-pumped, gas-cooled solid-state lasers a candidate for taking lasers beyond NIF to the production of unlimited electrical power based on inertial fusion energy.

In a similar vein, the article on metallic hydrogen (p. 12) reports on a recent Laboratory achievement with promising, significant implications for improving the laser targets that will be used in NIF, broadening their performance range and making them capable of higher performance. The revised information about the equation of state of hydrogen revealed by the Laboratory’s hydrogen metallization studies will contribute to the refinement of the hydrogen-isotope-filled targets to be used in the lasers that will make inertial fusion energy a reality.

Different as these two articles are, they have a similar subtext: The achievements they discuss illustrate the emphasis of Laboratory and the Laser Programs on forward-looking research management that plans well ahead for the future implications and applications of the scientific research and development done at Livermore. This research management philosophy is also what makes Lawrence Livermore a continuing key contributor to the global advancement of science and its most important applications.

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Taking Lasers beyond the National Ignition Facility

By the year 2005, the National Ignition Facility is expected to achieve fusion ignition—a major step on the road to producing electricity by fusion. Now the Laboratory has developed and tested new diode-pumped laser technology that increases both the power of lasers and their ability to fire rapidly. These advanced capabilities promise to help us achieve the ultimate goal of producing electricity by inertial confinement fusion.

LIKE computers and stereo equipment, state-of-the-art lasers continuously are improved by new developments. In fact, the laser's state of the art is being enhanced by a relative of one of the components used in CD players—the laser diode.

The laser diode, which produces purer monochromatic light than a flashlamp's full-spectrum of white light, is a candidate for taking the technology of Lawrence Livermore National Laboratory's planned National Ignition Facility (NIF) one step further. This technology, which can increase shot rates by up to 100,000 times, may enable us eventually to produce electricity by inertial fusion energy (IFE).[1]

NIF is one of the key components of stockpile stewardship, our national strategy to maintain nuclear competence without underground testing.[2] It is based on a flashlamp-pumped laser capable of delivering 1.8 megajoules of energy directly or indirectly onto a target within a few billionths of a second.[3] This energy

will induce plasma temperatures of millions of degrees and, in the case of indirect-drive targets, create intense soft x-rays that can compress a deuterium–tritium pellet to high-density and high-temperature to realize ignition by inertial confinement fusion (ICF)—a feat we expect NIF to achieve in about the year 2005.

NIF will fire approximately once every 4 to 8 hours, which is appropriate for the needs of ICF in the research stage and of stockpile stewardship. However, future ICF needs could call for shot rates of once every few minutes, and the ultimate use of ICF—to produce electric power—will require 5 to 10 shots per second, an increase of over 100,000 times compared to the shot rate achievable with state-of-the-art fusion laser technology. Can a fusion laser driver operate at this much higher repetition rate? Lawrence Livermore's advanced laser design and small-scale experimental results indicate yes.

To date, all of the highest energy laser facilities have been based on flashlamp-pumped neodymium-doped glass (Nd:glass) lasers because they are most amenable to large-scale deployment and they provide the flexibility in output characteristics needed for ICF and weapons-related experiments. However, the completion of NIF, followed by the prospect of fusion ignition in the laboratory within the next decade, prompts the question of what technology will best meet our nation's future needs.

Figure 1, which illustrates how the output energy of solid-state lasers has progressed over the last two decades, shows that we are considering a shift from flashlamp-pumped to diode-pumped solid-state lasers, with the objective of developing an advanced technology to provide "shots on demand" for ICF and stockpile stewardship. In fact, the diode-pump concept is ready to be developed for a broad array of near-term (kilojoule-level) Department of Energy and Department of Defense missions, as well as for longer-term megajoule applications.

Advanced Laser Beamline

The next step in developing diode-pumped laser technology is to build a prototype beamline (i.e., a beamlet) of an advanced laser facility within the next five to ten years (Figure 2). The basic components of this laser are the diode-pump arrays, ytterbium-doped strontium–fluorapatite (Yb:S–FAP) crystals, and a gas-cooling system for these crystals to allow an increased repetition rate. The facility would be capable of generating 1 kilojoule of energy on-target, at a repetition rate of

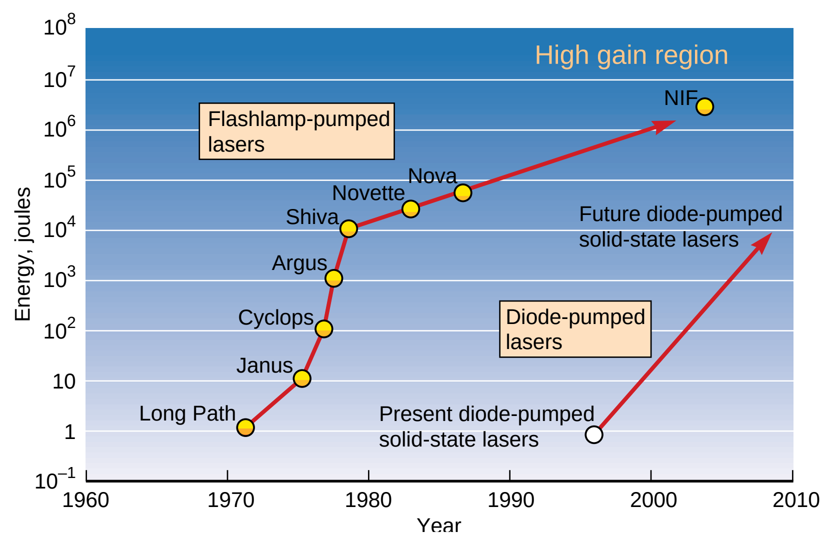

Figure 1. Maximum output energy of various LLNL laser fusion systems. Neodymium-doped glass laser technology will culminate with the construction of the National Ignition Facility, and next-generation diode-pumped laser technology will require development before it becomes relevant to high-energy/high-density physics experiments.

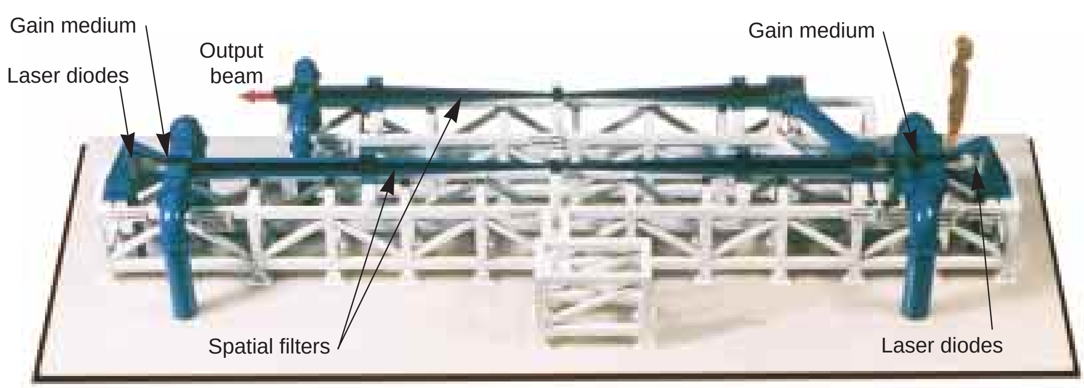

Figure 2. Model of a 1-kilojoule future "beamlet," based on diode-pumped solid-state laser technology, gas cooling of the laser slabs, and ytterbium-doped strontium–fluorapatite gain medium.

up to 10 hertz, with a "wall-plug efficiency" of approximately 10%.

Figure 3 is a photograph of an LLNL-developed laser diode package containing a high-power laser diode array. This technology produces monochromatic light output (single wavelength) rather than the white light characteristic of flashlamps (where all colors are represented in the output), leading to higher efficiency operation and reduced heating of the laser crystals. Among the other crucial advantages that laser diodes offer over flashlamps is that they will be able to fire ten billion times without being replaced, while large flashlamps can offer only about 100,000 shots. We have already demonstrated one billion shots for diodes produced in our laboratories.

Laser diodes are revolutionizing telecommunications, where they are deployed in optical amplifiers for undersea applications (with anticipated 30-year operating lifetimes), CD players, and high-speed computer networks. Using diode-pump sources at the megajoule-scale of fusion lasers, however, requires high peak power (large arrays of diodes rather than the single diodes commonly employed in industry today). The cost of the diodes must therefore be reduced to a "dime per watt," compared to the "dollars per watt" presently available.

Our analysis of diode production costs suggests that this cost reduction is plausible but will require a large-scale application, such as laser fusion, to drive down the cost of diodes. Laser diodes also permit the long-term vision of electrical power production with fusion by virtue of their very high electrical-to-optical conversion efficiency (more than 50%). Thus, the overall efficiency of the diode-pumped solid-state laser can be more than 10 to 20%, because of the high efficiency of the diodes and the efficient manner in which their output can be delivered to the Yb:S–FAP crystals.[4]

The Yb:S–FAP crystals serve as the "gain medium," which amplifies the light beam as it propagates through the laser chain. These novel crystals, invented at LLNL in 1991 and recognized with an R&D 100 Award, essentially will supplant the Nd:glass used in Nova and NIF. The main advantage of Yb:S–FAP crystals is that they can store four times as much energy as Nd:glass for a given energy pumping rate.[5] They are also better able to conduct away excess heat than is laser glass.

Another crucial new technology that enables the high repetition rate needed for fusion is the gas-cooled slab,[6] as sketched in Figure 4. Cooling is needed because all lasers produce waste heat, which must be removed without disturbing the sensitive optics. Lawrence Livermore has developed the technique of flowing helium gas across the laser crystal surface in a turbulent manner at about one-tenth the speed of sound to conduct heat away from the crystals. Helium gas is employed because it has high thermal conductivity and causes only insignificant optical distortions. The heat and light pass through the same surface. Most importantly, the gas-cooled slab design has the added advantage of being readily scalable by increasing the area of the slab. This scalability is a critical issue because fusion lasers will operate in the megajoule range in an electrical power plant.

Prototype Applications

The most energetic diode-pumped solid-state lasers today generate about 1 joule of output energy in a pulse lasting

Figure 3. Laser diode array produced at LLNL, based on high-peak-power laser diode bars, efficient microchannel cooler packaging, and high-brightness microlens collimators.

a few nanoseconds. We believe a prototype beamline operating at about 1,000 joules (or even 100 joules) would have near-term utility for experiments and testing relevant to plasma physics and ICF. This facility could be run up to 10 hertz in repetition rate, although for most plasma physics and laser science experiments conducted today, it essentially will be capable of providing "shots on demand." Examples of plasma physics experiments we would perform at the prototype beamline facility include:

- Average-power x-ray lasers.
- Average-power x-ray sources for imaging.
- Laser-induced shock physics and laser plasma interaction studies.
- X-ray diagnostics development.

Optical experiments include:

- Large-area multishot damage testing of NIF optics.
- Debris shield survivability studies.

Other important uses of a kilojoule facility are:

- Calibrating of x-ray cameras and other diagnostics.
- Prototyping the design of a future megajoule facility.
- Testing advanced laser concepts for inertial fusion energy.

Small-Scale Demonstrations

One of the recent outcomes of the experimental program has been the gas-cooled slab testbed, shown in Figure 5.[7] This device integrates the accomplishments we have made over the last ten years: long-storage-time Yb:S–FAP gain medium, high-power laser diode arrays, and turbulent gas cooling. The laser testbed demonstrates solutions to the technical hurdles that are unique to future high-repetition-rate fusion lasers. The laser has produced 50 watts of power output in a tabletop package, a power regime that is regarded as significant by the laser community. At 50 watts, the thermal load being transferred to the helium gas (flowing at

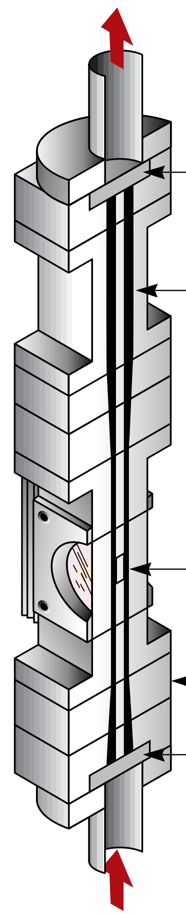

Figure 4. Schematic drawing of the gas-cooled slab concept illustrating the high-speed helium gas flow across the optical aperture that the laser light also traverses.

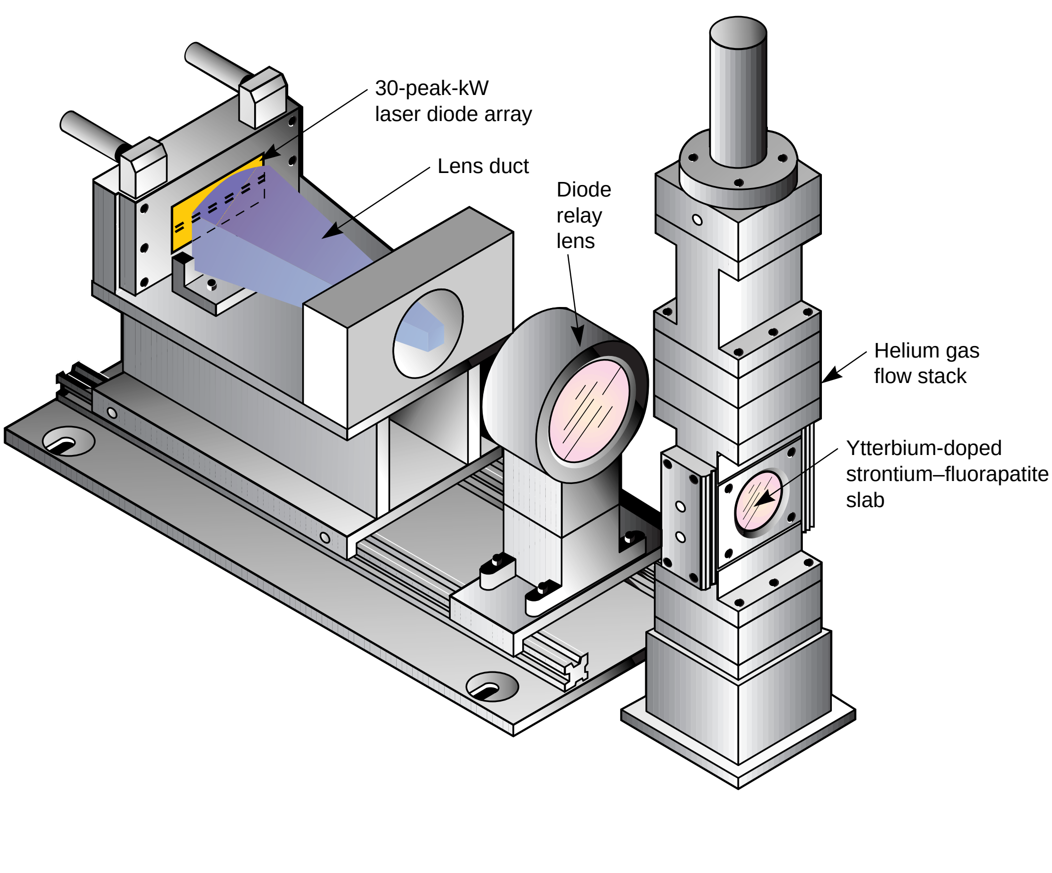

Figure 5. The first integrated laser module based on the use of LLNL laser diode arrays, gas cooling, and ytterbium-doped strontium–fluorapatite gain medium. This gas-cooled testbed is a subscale demonstration of the technology relevant to future advanced lasers for inertial confinement fusion and stockpile stewardship.

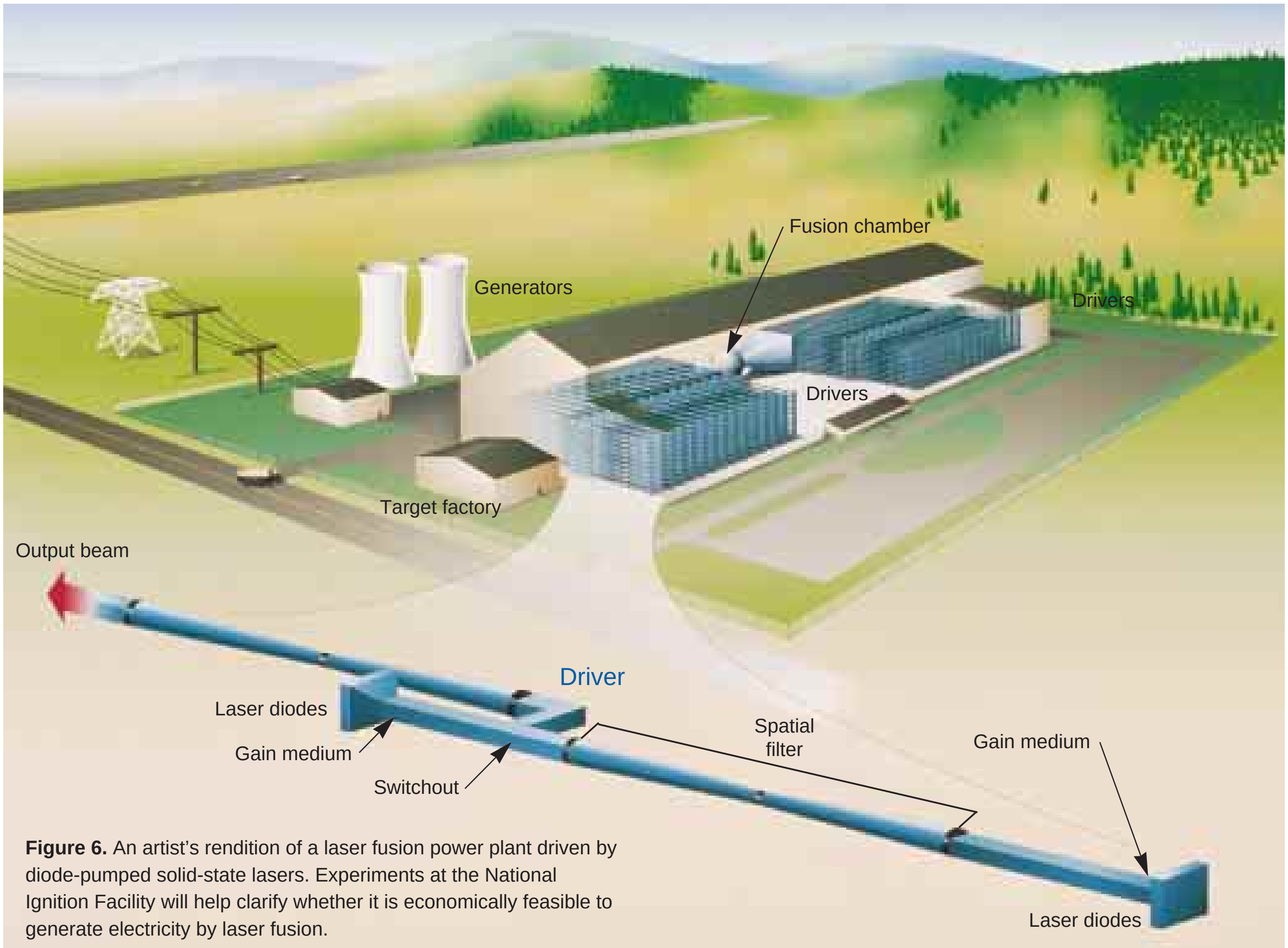

Figure 6. An artist's rendition of a laser fusion power plant driven by diode-pumped solid-state lasers. Experiments at the National Ignition Facility will help clarify whether it is economically feasible to generate electricity by laser fusion.

about 0.1 Mach) is more than 3 watts per square centimeter. Our estimate of the requirement for a megajoule system running at 10 hertz is about 1 to 2 watts per square centimeter. The Yb:S–FAP laser slab did not fracture until more than 50% of the theoretical stress limit of the material was reached, which is about two times higher than required for future megajoule ICF facilities.

Another crucial issue of diode-pumped technology involves the overall efficiency of the system. Our small Yb:S–FAP diode-pumped laser has yielded an overall electricity-to-light conversion efficiency of more than 10%.[8] We are working to correct some problems, such as impurity absorptions in the laser crystals and unoptimized optical coatings, and we believe that we can achieve an efficiency that exceeds 20% in long-pulse operations. To achieve this objective, the crystals and coatings need to have optical damage thresholds of greater than 10 joules per square centimeter for 10-nanosecond pulses. We have found that selected crystals that are completely free of defects meet this criterion, although increased quality control will be needed to attain this standard routinely.

Energy Production Is Goal

An ultimate goal of all laser fusion efforts is to tap this inexhaustible source of producing electricity. Figure 6 is an artist's rendition of a laser-driven ICF power plant, which consists of four parts: (1) drivers, which provide many intense laser beams focused onto targets, which are mass-produced in (2) the target factory and positioned in (3) the fusion chamber. When the beams hit the targets, bursts of fusion energy at 5 to 10 pulses per second are produced to operate (4) conventional steam turbine generators.

Success in reaching the goal of electric power production using IFE is complicated by a great number of concerns that reach far beyond the laser driver. One is the cost of the power produced. Using the same kind of calculations that are used to model the NIF and Nova lasers, we predicted that electricity produced by ICF would cost about 8.6 cents per kilowatt-hour.[4] While this is higher than the cost of power produced today by fossil fuels

(5 to 6 cents per kilowatt-hour), future energy costs from traditional nonrenewable sources are uncertain.

The highest risk issues confronting the prospect of ICF-based power generation are the level of achievable target gain and the survivability of the final optic. One of the primary missions of NIF is to attain sufficient target gain to produce ignition. The final optic plays a critical role because this material must efficiently transmit ultraviolet light while simultaneously incurring the wrath of the high-energy neutrons and gamma rays that emanate from the target and the target chamber.

The best prospect for the final optic is heated fused silica. Although the rates at which the final optic will be bombarded by radiation in NIF are significantly less than those for inertial fusion energy (about 50 kilorads per year versus 50 kilorads per second!), the basic physical mechanisms may be similar. Figure 7 shows that different types of fused silica have significantly different levels of radiation-hardness, as indicated by the blackening of the material. This blackening can be avoided easily, however, by choosing fused silica materials that are free of aluminum impurities. Our investigation also revealed that germanium impurities also reduce radiation hardness.

After determining that certain fused silicas had neither aluminum nor germanium impurities, we identified the intrinsic defects that were created solely by the neutrons and gamma rays. Our light absorption measurements indicate that, if the appropriate type of fused silica is used, the absorption loss at the NIF laser wavelength of 0.35 micrometers will be 1% after 30 years of operation, which is the life expectancy of NIF. In another series of experiments, we determined that defects that are formed by the neutrons and gamma rays are annealed, or repaired, if the optic is held at an elevated temperature. At 400°C, the defects should not cause undue absorption of the laser light—even at the radiation dose rate predicted for a power plant.

Figure 7. Picture of various fused silica samples that received radiation doses comparable to those predicted for the final optic at the National Ignition Facility. On the basis of our studies, the appropriate “radiation-hard” optical materials were identified.

The beamline for a fusion power plant, including the heated fused silica final optic, is shown schematically in Figure 8. It is similar to the prototype beamline of NIF in that a pulse (about 1.7 joules) is injected and then allowed to traverse the multipass amplifier four times before being ejected at about 10 kilojoules. However, the higher gain and energy storage possible with diode pumping and Yb:S–FAP gain crystals eventually will allow for better reliability, beam quality, compactness, and efficiency, all of which are necessary in a power plant. This beamline is considered capable of an efficiency approaching 10% for on-target properly conditioned laser light, a level upon which the feasibility of a working power plant critically depends. Figure 8 also depicts the gas cooling of the laser crystals and the harmonic conversion crystals (which nonlinearly convert the 1.047-micrometer fundamental output wavelength of the laser to the third harmonic at 0.35 micrometers). Both technologies together with the heated fused silica final optic are fundamental to producing electricity based on laser

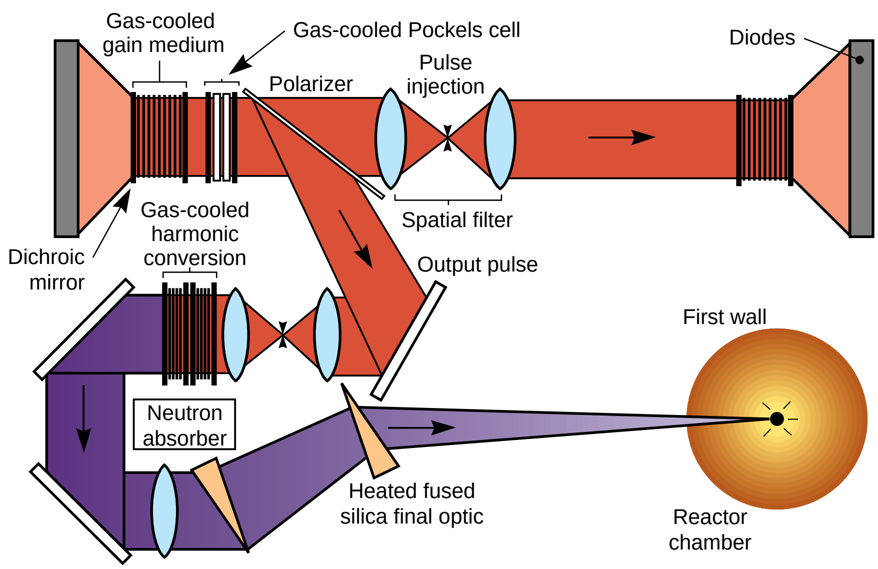

Figure 8. Schematic of a beamline designed on the basis of laser physics, achievable performance specifications, and reasonable cost. The basic architecture involves a multipass amplifier and frequency conversion (as does the National Ignition Facility), as well as the technology enhancements discussed in this article.

fusion. When 5,175 beamlets are grouped in 345 beamlines, the system could deliver 3.7 megajoules on-target. An assumed target gain of 76 would lead to gross energy production of 300 megajoules with 40 megajoules per shot recycled to power the laser and other systems.[3]

To and beyond Ignition

While the flashlamp-pump technology of NIF will achieve ignition and be used to explore weapons issues during the beginning of the next century, diode-pumped solid-state lasers represent a promising laser driver beyond NIF. Other fusion driver options exist with the potential of effecting fusion energy production—the heavy-ion accelerator is one example; light-ion accelerators and krypton–fluoride lasers are others.[1] And each has complementary risks and benefits for fusion energy production.[9] At this juncture, however, many physics and engineering issues need to be resolved for any option. The applicability of these options to driving targets will become clearer during the next decade. The promise of fusion for energy production and the relative utility of different driver options is best left as an open question until after NIF ignites a target. Yet the diode-pumped option is certainly a major contender as the vehicle for the ultimate application of NIF technology—the production of unlimited electrical power from inertial confinement fusion.

In the near-term, uses for advanced high-repetition-rate lasers also abound. In addition to offering us a pathway to future inertial fusion studies and stockpile stewardship applications, our small-scale experiments attest to the scientific viability of diode-pumped solid-state lasers for fusion, as do the synergistic laser development efforts in support of numerous military and civilian applications (see the box on p. 10).

Key Words: diode-pumped solid-state lasers, final optic, gas-cooled slab (GCS), gain medium, inertial confinement fusion (ICF), inertial fusion energy (IFE).

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